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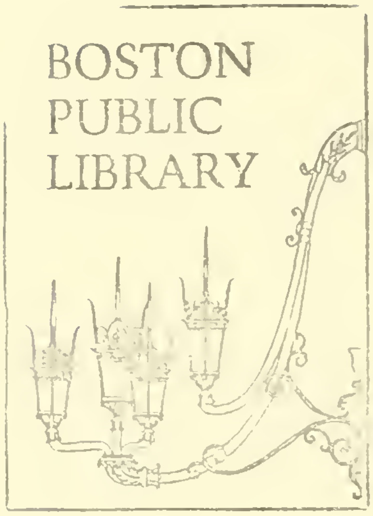

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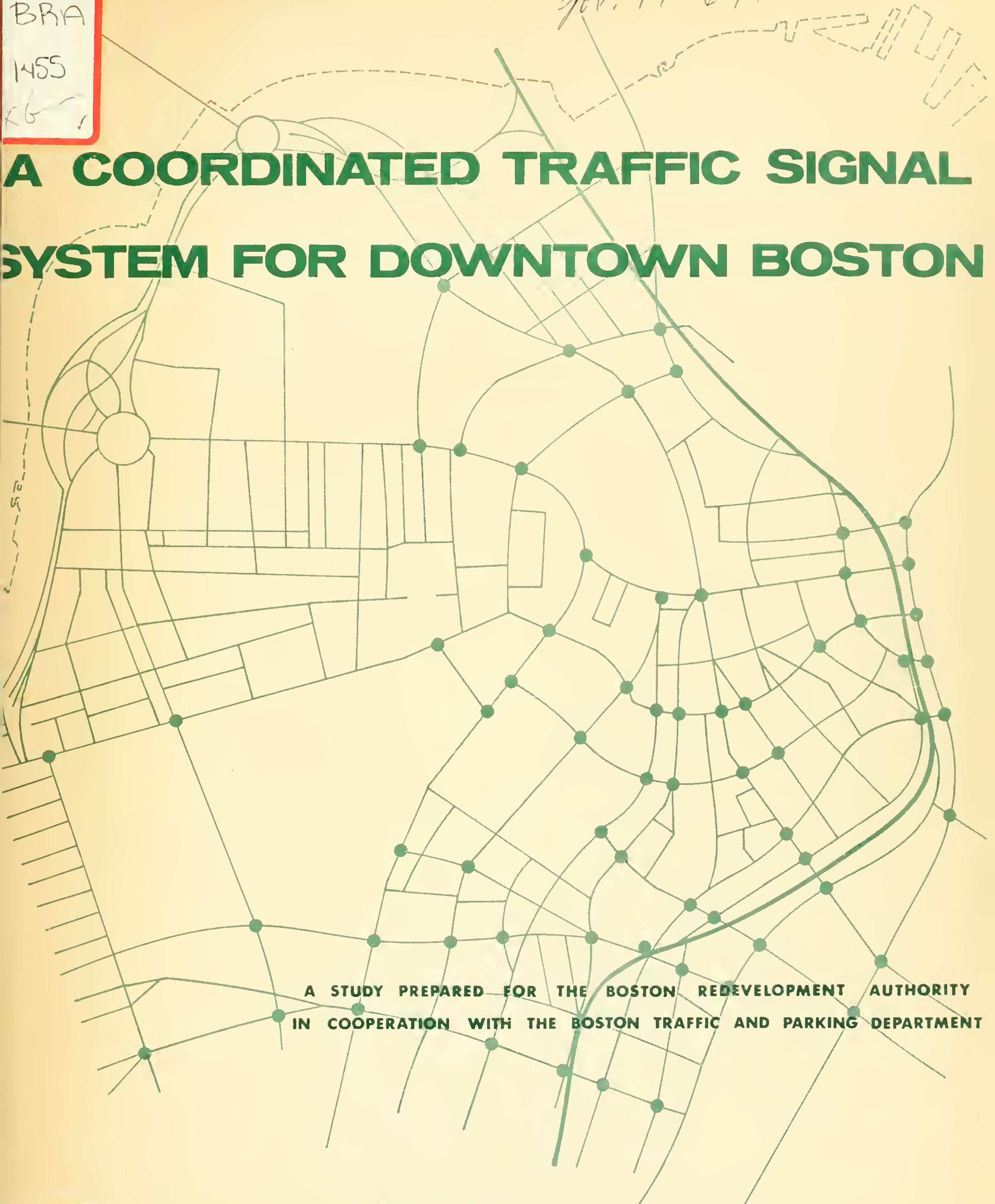
A COORDINATED TRAFFIC SIGNAL SYSTEM FOR DOWNTOWN BOSTON



A STUDY PREPARED FOR THE BOSTON REDEVELOPMENT AUTHORITY
IN COOPERATION WITH THE BOSTON TRAFFIC AND PARKING DEPARTMENT

FFIC RESEARCH CORPORATION

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A COORDINATED TRAFFIC SIGNAL SYSTEM FOR DOWNTOWN BOSTON

Prepared for

THE BOSTON REDEVELOPMENT AUTHORITY

in cooperation with

THE BOSTON TRAFFIC AND PARKING DEPARTMENT

by

TRAFFIC RESEARCH CORPORATION

A study to determine the most desirable signal controllers, cycle lengths and settings for a coordinated traffic signal system in downtown Boston, Massachusetts.

October, 1965

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1. INTRODUCTION

The primary objective of this study is the development of a traffic signal control system, with a timing program which is designed to reduce traffic delay to a practical minimum.

The study area, comprising a large portion of downtown Boston, contains 68 signalized intersections.[1] Most of these signals are proposed signals; changes are being made in intersection geometry and in phasing, and new signals are being installed at some intersections where they do not now exist. Volumes, too, are projections to the time after completion of the various urban renewal projects located in, or bordering on, the study area. The projects include: the Central Business District project; the Government Center project; the Waterfront project; the West End project; and the South Cove project.

The study area was resolved into a system of 150 links between signalized intersections. A number of routes through the system were designated by the Boston Redevelopment Authority as priority routes; i.e., it was more important to reduce delays on these routes than on routes not given any priority.

Traffic Research Corporation utilized for the study a technique it has developed which, based on a method of delay minimization, determines optimum offsets for all signals in a network of any configuration. Input to the program are: the geometry of the system; volumes on each of the links; cycle lengths; phase splits (proportions of "go" time given to the various approaches at an intersection); importance factors (to indicate relative priorities of the various routes); and desired differences in offsets of adjoining intersections (based on travel speeds, distances between intersections, and time required to clear standing queues).

Output are the optimized offsets for each intersection and a delay propensity factor for the system and for each individual link. Also available as optional output, for comparison purposes, are delay propensity factors for the existing system and for the individual links, (This optional output does not affect the optimization process, but does require existing offsets to be input to the program). The "delay propensity factor" represents the tendency to produce delay due to discrepancies between ideal and actual differences in offset between adjoining signalized intersections, and is given in terms of seconds per vehicle per signalized intersection. Other factors contributing to delay, such as marginal friction and overloading of the system, are largely independent of signal

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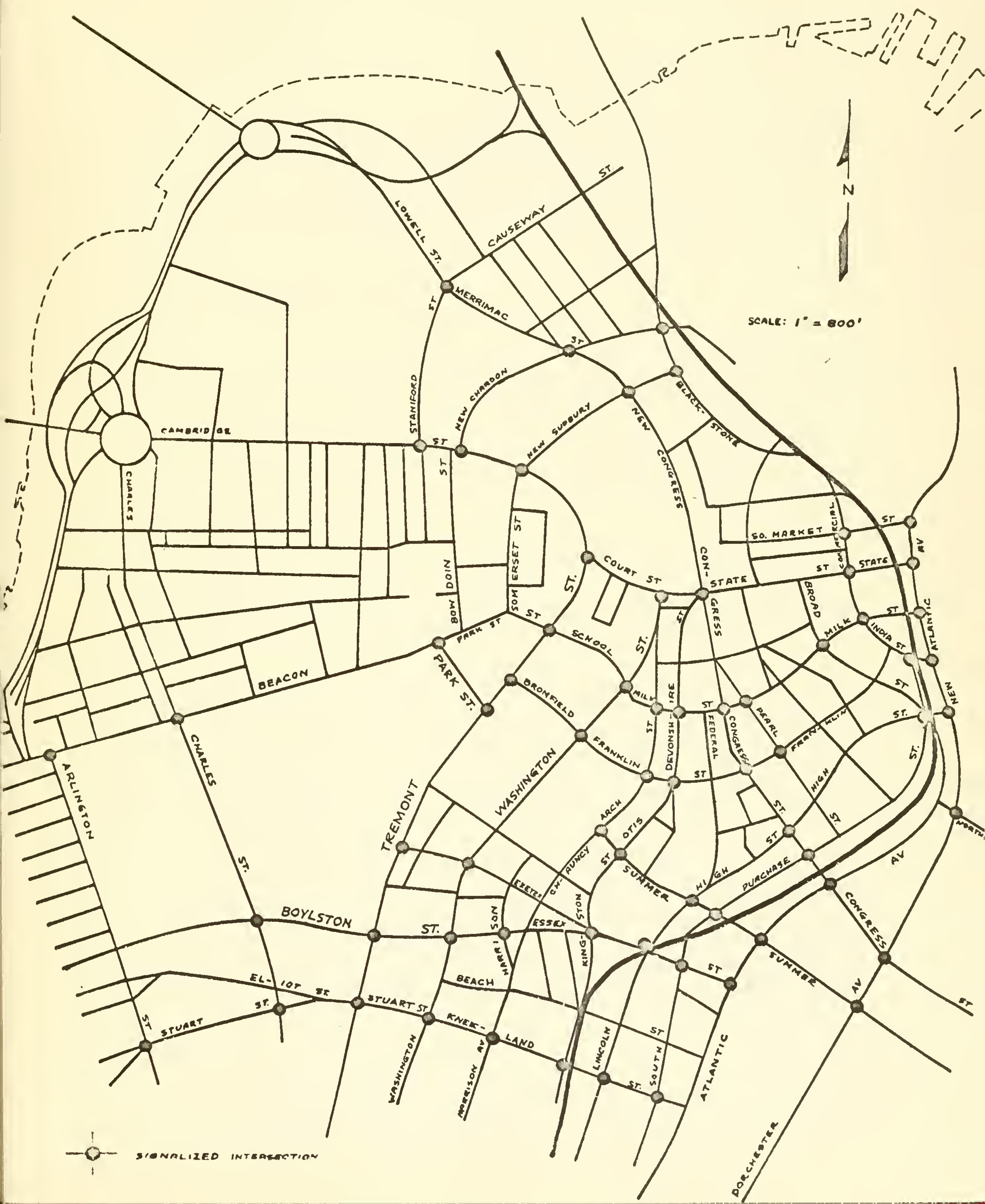
[1] See Figure 1. Map of the Study Area.

FIGURE 1. MAP OF THE STUDY AREA.



timing, and are not reflected by the delay propensity factor.

Because of the variations in traffic flow patterns, the optimization program was run separately for various times of day; using a coarse breakdown into four time periods, and a fine breakdown into twelve time periods. The purpose of this was to determine whether the finer breakdown would produce a sufficient decrease in delay to warrant additional expenditures for more flexible signal equipment.

2. RECOMMENDATIONS

On the basis of the present level of technology and the projected traffic flows furnished Traffic Research Corporation, it is recommended that the City of Boston proceed with the installation of a multi-dial fixed-time traffic signal system which will suit the immediate and near future needs of downtown Boston. It is also recommended that the City initiate an engineering study to plan how this system should best develop into a computer controlled system which future traffic demands may require.

It is the understanding of Traffic Research Corporation that, upon special order, six-dial controllers could be obtained with up to five offsets and four splits available per dial. It is recommended that this type of controller be obtained for the fixed-time system.

The recommended timing patterns for the fixed-time system require five dials, and utilize from 1 to 4 offsets and from 1 to 4 splits per dial. Cards containing the recommended splits, offsets, and cycle lengths for each of the 68 signalized intersections in the study area have been presented to the Boston Redevelopment Authority, accompanied by space-time charts for all recommended timing patterns for thirteen major routes through the area.[1]

The high volumes in the study area, which cause intersections to frequently operate at or near capacity, prompt the following additional recommendations: (1) pedestrians should be allowed to cross with turning vehicles; and (2) certain phasing and routing changes should be implemented at several intersections. (This second recommendation is delineated in more detail in Section 3.b, dealing with intersection improvements).

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[1] See Appendix, Table 4. Sample Operation Schedule. Also, Table 5. List of Routes for which Space-Time Charts have been Presented to the BRA.

3. STUDY PROCEDURE

a. Capacity checks

Data supplied by the Boston Redevelopment Authority includes maps of the intersections, phasing diagrams, and half-hour traffic counts for each intersection from 7:00 A.M. to 12:00 Midnight (including turning movements). These volumes were projections based on the completion of the several urban renewal projects located in, or bordering, the project area. In addition, a map of the study area at a scale of 1" - 100' was provided, and desired travel speeds on each of the routes was indicated.

Minimum times for pedestrian crossings were set at 7 seconds plus clearance time. Pedestrian clearance time was calculated as walking time, at 4 feet per second, from the curb or median pedestrian island to the center of the far travel lane. No conflicts were to be allowed between vehicle movements and pedestrian movements. (As noted in the previous section, TRC recommends modification of this restriction to enable pedestrians to cross with turning vehicles).

For the various approaches to each of the intersections in the study area, Traffic Research Corporation graphed the traffic volumes over the day. Using these graphs, plus data from the 1964 Downtown Boston Cordon Count[1] and the 1963 BRPP Home Interview Survey[2], the day was divided into four time periods: an A.M. peak period; a Midday period; a P.M. peak period and an Evening period.

Using the peak half-hour flows for the A.M. and P.M. periods, phase splits were calculated for each intersection by assigning the available green time to the various phases in proportion to the volumes of the critical flows occurring during each phase. The green times per hour were computed, and capacity checks on the individual intersections were then carried out. These were in the form of computed loadings of vehicles per lane per hour of green time. On a 90-second cycle, 27 of the 68 signalized intersections were found to experience a loading during the A.M. and/or P.M. peak periods greater than 1200 vehicles per lane per hour of green time.

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[1] Boston Traffic and Parking Commission. 1964 Cordon Count, Downtown Boston

[2] Wilbur Smith & Assoc. BRPP Home Interview Survey -- Draft Final Report, September, 1964.

Twenty-three of these were loaded with over 1400 vehicles per lane per hour of green time. On a 120 second cycle, the corresponding figures were 21 and 16 intersections, respectively.

b. Intersection improvements

Attempts were made, in cooperation with the Boston Redevelopment Authority, to overcome the problems brought to light by the capacity checks. Towards this end, the following phasing, geometry, and routing changes were worked out:

(1) Install a separate turning lane for the right turn from Congress St. northbound onto Sudbury St. eastbound;

(2) Add a lane on Summer St. by eliminating the island on that street at the westbound approach to the intersection of Summer St. and Atlantic Ave.;

(3) Prohibit left turns from Commercial St. southbound onto Milk St. eastbound, and route this traffic around the Customs House---i.e., right onto State St., left onto India St., and left onto Milk St.;

(4) Convert High St. between Atlantic Ave. and New Atlantic Ave, to one-way flow westbound from New Atlantic Ave., and split into two phases the straight-thru and left-turning (onto High St.) northbound traffic on New Atlantic Ave.;

(5) Provide an exclusive pedestrian phase at the intersection of Commercial, South Market, and Mercantile Streets, and allow the northbound traffic on Commercial St. to turn left during the green phase for westbound traffic on South Market St. and to turn right during the green phase for southbound traffic on Commercial Street;

(6) Provide an exclusive pedestrian phase at the intersection of New Atlantic and India Streets, combine all northbound and southbound traffic on New Atlantic Ave. into one phase, and combine all eastbound and westbound traffic on India St. into one phase;

(7) Eliminate the advanced green phase for westbound traffic on Summer St. at the intersection of Summer, Purchase, and South Streets; and

(8) Eliminate the separate turning phase at the intersection of Essex and South Streets for left turns onto South St., and provide one combined phase for all traffic entering the intersection from the eastbound and westbound Essex St. approaches.

It was also recommended that pedestrians be allowed to cross with turning vehicles. By relieving many intersections of the necessity of providing multi-phasing or an exclusive pedestrian phase, more green time could be allotted to vehicle phases, thus further reducing capacity problems.

Several intersections remain whose geometry does not appear adequate to handle the traffic volumes projected for them. These are the three intersections on New Atlantic Avenue between Northern Avenue and Summer St., and the five intersections on Stuart St.-Kneeland St. between Tremont St. and Lincoln St. It was agreed by Traffic Research Corporation and the Boston Redevelopment Authority that the operation of these intersections will have to be carefully watched when the traffic signal system for these areas is installed.

c. System optimization

For each time period, defined by the original breakdown of the day into four periods, as well as by the finer breakdown into twelve periods, the optimization procedure was as follows. Average half-hourly volumes were computed, and minimum cycle lengths, based on capacity restrictions, were determined. (This calculation utilized work done by Greenshields,[3] with allowances being made for commercial vehicles and random arrivals). Phase splits were next calculated for various acceptable cycle lengths, and Traffic Research Corporation's optimization technique was applied.

Basically, the optimization technique is designed to minimize delay in the following manner. For each link in the system there is input a desired difference in offset (i.e., the desired time interval between the beginning of green at the upstream intersection and the beginning of green at the downstream intersection) which is based on link distance, link travel speed, and an adjustment to clear standing queues at the downstream intersection. If these desired differences in offset could all be obtained, traffic would move through the intersections encountering a minimum number of red lights, and delay would be minimized. Due to geometrical constraints, however, it is usually not possible to achieve the desired or ideal difference in offset for each of the links in the system.

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[3] B. D. Greenshields et al, Traffic Performance at Urban Street Intersections. Yale University. Bureau of Highway Traffic. Technical Report 1. New Haven, Conn. 1947.

Applying the optimization technique, the offset pattern of the system is adjusted so as to get as close as possible to the ideal set of offsets, each link being weighted in accordance with the volume on the link and with an "importance factor" which may be applied to it. The final pattern arrived at in this manner is designated as the optimal pattern; i.e., as that pattern which minimizes total delay in the system.[4]

The importance factors are used to indicate relative priority of the various links: high where it is especially important to achieve good progression; and low or fractional where, for example, a high proportion of turning movements negates much of the importance of coordinating a link. For the Boston study, several identical systems were optimized with different sets of importance factors, and that set of values was selected which yielded reasonable progressions on the high priority routes without affecting too adversely the remainder of the system.

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[4] A more detailed description of the optimization calculation is included in Appendix A.

4. RESULTS

a. General

The optimization technique, programmed for the computer, was run a total of fifty-four times for the various combinations of time periods, cycle lengths, and priority assignments. The results for each of the runs are summarized in Table 1 in Appendix A.

From the results of these runs, the following observations concerning the study area can be made. First, shorter cycle lengths tended to produce lower delay propensity factors. For the fine breakdown (12 time periods), an average reduction in cycle length of 12.5% (occurring in the range of cycle lengths from 70 sec. to 130 sec.) was accompanied by an average reduction in delay propensity factor of 7.9%. And second, a reduction in the number of offset patterns over the day significantly increased the delay propensity factors. When the time periods in the fine breakdown (12 time periods) were run with their own optimized offsets, and then with offsets optimized for the coarse breakdown (4 time periods), the delay propensity factor was increased, on the average, by 12.6%.

Delays were calculated for complete sets of optimal fixed-time timing patterns over the (17-hour) day. These timing patterns were developed for various types of locally available traffic signal controllers which are designed for, or could be used for, fixed-time operation, including: the standard 3-dial controller; two types of conventional traffic responsive controllers (i.e., sampling detector operated, taking several cycle lengths to respond); and two types of 6-dial fixed-time controllers. The delays associated with each of these controllers are graphed in Figure 2.[1]

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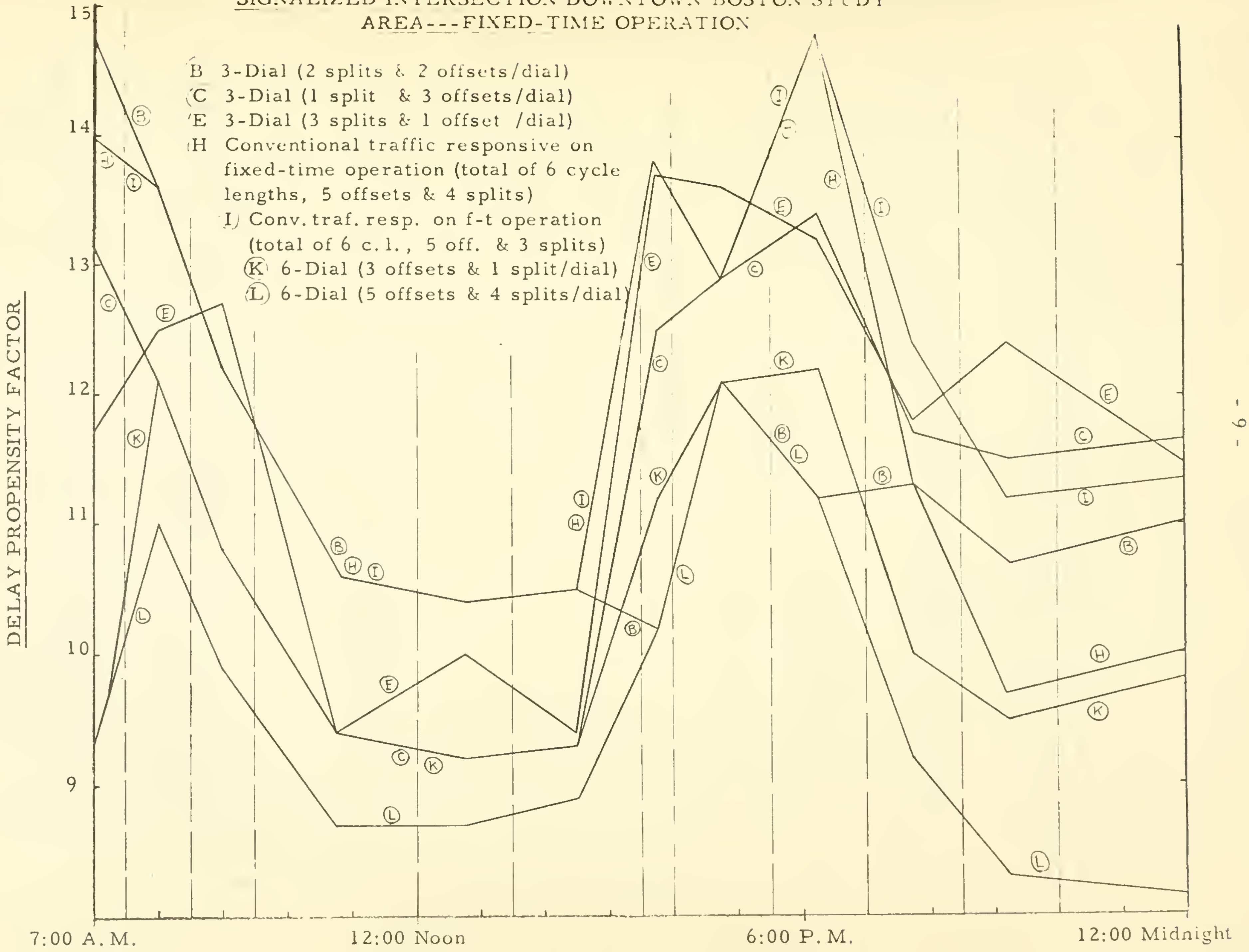
[1] See also, in Appendix B, Tables 2 and 3.

FIGURE 2. ESTIMATED DELAY PROPENSITY FACTORS FOR 12 TIME PERIODS FOR THE SIXTY-EIGHT SIGNALIZED INTERSECTION DOWNTOWN BOSTON STUDY AREA---FIXED-TIME OPERATION



The average delay propensity factors over the day, for each type of controller, for the 68 signalized intersection study area in downtown Boston, are listed below. The figures for traffic responsive or traffic actuated operation are subject to the constraints discussed in Section 4.c, while the fixed-time modes are discussed in Section 4.b.

Average Delay Propensity Factors for Various Types of Controllers, Estimated from BRA Projected Volumes for Downtown Boston Study Area (68 Signalized Intersections)

Conventional traffic responsive (sampling detector operated, taking several cycle lengths to respond) under fixed-time operation (total of 6 cycle lengths, 5 offsets, and 3 splits)	12.0
Conventional traffic responsive under fixed-time operation (total of 6 cycle lengths, 5 offsets, and 4 splits)	11.8
3-Dial (3 splits and 1 offset per dial)	11.5
3-Dial (2 splits and 2 offsets per dial)	11.4
3-Dial (1 split and 3 offsets per dial)	11.2
6-Dial (1 split and 3 offsets per dial)	10.4
6-Dial (5 offsets and 4 splits per dial)	9.7
Conventional traffic responsive	10.8
Computer-controlled traffic responsive (instantaneously reacting, with detectors at most intersections)	9.2

b. Delay estimates for fixed-time systems

The standard 3-dial controller normally comes with 1 split and 3 offsets per dial; however, it is usually possible to trade off an offset for a split by re-wiring. Timing patterns were developed for three offset-split combinations on the 3-dial controller, but the delay propensity factors remained relatively constant.

The conventional traffic responsive controllers (discussed in more detail in Section 5.b) were not designed for fixed-time operation.

It is possible, though, (albeit not recommended), to use these without their traffic responsive features. Under fixed-time operation, these systems produced delay propensity factors in the downtown Boston study area slightly higher than those produced by the 3-dial systems. This is attributable to the fact that, while they offer a greater number of cycle lengths and a theoretically greater number of possible offset-split combinations than the 3-dial controller, many of the combinations are usually impractical. Splits and offsets are given as percentages of cycle length, and a given split-offset combination will generally not combine with all six cycle lengths to produce settings which will effectively reduce delay. Some offset-split combinations, in fact, will probably be ineffective in this respect regardless of the cycle lengths used. For example, with these traffic responsive controllers, only three or four time periods can have their own optimized split and offset patterns, while with a 3-dial controller wired for 2 splits and 2 offsets per dial, 6 time periods can have their own optimized settings.

Use of the 6-dial controller with 1 split and 3 offsets per dial resulted in a decrease in delay propensity factor of 6.4% over the best usage of the 3-dial controller; or (as indicated in Table 3 in Appendix B), on the basis of a five-day (17 hours/day) week, a decrease of 74,760 vehicle-hours per year in the 68 signalized intersection downtown Boston study area. Similarly, the delay propensity factors associated with the more flexible (5 offsets and 4 splits per dial) 6-dial controller were 12.7% lower (by 147,470 vehicle-hours per year) than with the 3-dial controller; and 6.7% lower (by 72,710 vehicle-hours per year) than with the 6-dial controller with 1 split and 3 offsets per dial.

The estimated cost of the more flexible 6-dial system (5 offsets and 4 splits per dial) for the study area is about $70,000 higher than the less flexible 6-dial system (1 split and 3 offsets per dial) and about $100,000 higher than a standard 3-dial system; or (based on a 20 year amortization and a 5% interest rate), about $5,500 and $8,000 higher per year, respectively. If an occupancy rate of 1.5 persons per vehicle is assumed,[2] and a person's time is valued at $1.25 per hour,[3] the use of the more flexible 6-dial system would result in a savings in time alone---excluding savings in vehicle operating costs and such intangibles as driver frustration---of about $136,000 per year over the less flexible 6-dial system, and about $277,000 per year over a standard 3-dial system.

An estimate of the amount of improvement over the existing system is impractical. The study area incorporates many changes in street patterns from the existing system, and of the 68 signalized intersections in the study area, only about ten to fifteen presently exist which will not be altered in some way. Some indication of the effectiveness

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[2] From Wilbur Smith and Assoc. Op. cit. Table B-3A. Vehicle Occupancy by Trip Purpose, Internal Survey --- Auto Trips.

[3] Minimum wage as specified in U.S. Fair Labor Standards Act (as of Sept., 1965).

of Traffic Research Corporation's optimization technique, however, as compared to manual signal timing techniques, can be obtained by looking at previous studies where "before" and "after" field studies were carried out. In the Spring of 1963, a preliminary traffic timing study was carried out in Detroit, Michigan, in a study area containing 29 signalized intersections. Test cars operated by the staff of the Detroit Traffic Department experienced a total delay of 38 minutes with the original settings, and were brought to a full stop 89 times. With the new settings, delay was cut to 22 minutes and the number of stops to 52, a 42% reduction in both quantities.

In a 79 signalized intersection area in downtown Hamilton, Ontario, the "before" splits and offsets had been recently updated as much as possible with conventional manual methods using time-space diagrams. As reported in an article in Traffic Engineering, June, 1964, the use of new signal settings generated by Traffic Research Corporation's programmed technique resulted in a 13% reduction both in delay and in number of stops.

c. Delay estimates for traffic responsive systems

Traffic Research Corporation's optimization technique is designed for, and can evaluate, fixed-time systems only. These, by their nature, are restricted to producting average settings for which it is sufficient to know average traffic conditions for specified time periods. To make predictions on the performance of traffic responsive signal systems, a great deal more information must be available about the variability of the traffic flows along the various streets, such as the magnitude and frequency of peak fluctuations above the average flows. This kind of information was not available for downtown Boston (and, in fact, is almost never available, except where a sophisticated computer controlled system is already in operation).

As a result, it was not possible to follow the operation of a signal system for the Boston study area through those variations that make a traffic responsive system necessary. In effect, only a pilot study of the type of traffic responsive control being evaluated could yield firm estimates of reductions in delay and of other operating benefits obtainable with such a system. Therefore, while slowly responding traffic signal systems can in some instances be evaluated as fixed-time systems over short periods of time, it requires a great deal of judgment in estimating improvements which these systems may provide. Consideration should be given to such factors as: the number of signals operating at or near capacity at any given time (when this number includes most of the intersections in an area, there would be little chance of gaining improvements with a traffic responsive system); the number of times that congestion occurs on some but not all

approaches at one or more intersections (it is often possible in a computer controlled system to redistribute traffic to produce smaller and less troublesome queues); and the extent to which factors other than those inherent in the flexibility of control may limit the effectiveness of a more sophisticated traffic signal system (e.g., bad habits of pedestrians).

The estimates made in Section 4.a of average delay propensity factors for traffic responsive systems are based not only on a review of traffic volumes for the study area, as far as they are available, but also on factors such as those mentioned above and on comparable experience gained elsewhere. For example, in a study carried out for the City of New York,[4] in an area of about 1.5 square miles bounded by 30th and 60th Streets and 2nd and 8th Avenues, the following reductions in delay over the then existing system were estimated.

Fixed-time (single setting) system set by space-time chart method	11%
Fixed-time (single setting) system optimized by computer program	22%
Fixed-time (3-dial) or conventional slowly reacting traffic responsive system	24%

(During prolonged periods (longer than 15 minutes) of abnormal traffic (differing from normal traffic by more than 40%) the traffic responsive system would be about 8% better than the 3-dial system).

Computer controlled instantaneously reacting traffic responsive system	34%

(This system would reduce unusual traffic fluctuations and have considerable capability for controlling congestion and for emergency operations. It could react to unusual situations within seconds and would, therefore, greatly out-perform the other systems during short or long periods of unusual traffic conditions).

In another study carried out in Toronto,[5] delays were measured on all four approaches to each of two intersections (chosen because of heavy usage and relative simplicity of layout) under fixed-time operation and under two forms of relatively sophisticated traffic responsive, computer controlled operation. Each of the three modes of operation

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[4] Traffic Signal Improvements in Mid-Manhattan. Report prepared by TRC for the Department of Traffic of the City of New York. Henry A. Barnes, Commissioner. 1962.

[5] The Control of Traffic Signals in Metropolitan Toronto with an Electronic Computer. A report on the pilot study of the automatic control of traffic signals conducted for the Traffic Engineering Department of the City of Toronto and the Municipality of Metropolitan Toronto by TRC, 1961.

was used during the morning and evening rush hours for five days. Delays obtained under the two traffic responsive modes were very similar, and the average delay (in seconds per vehicle) encountered by all vehicles using the two intersections is given below.

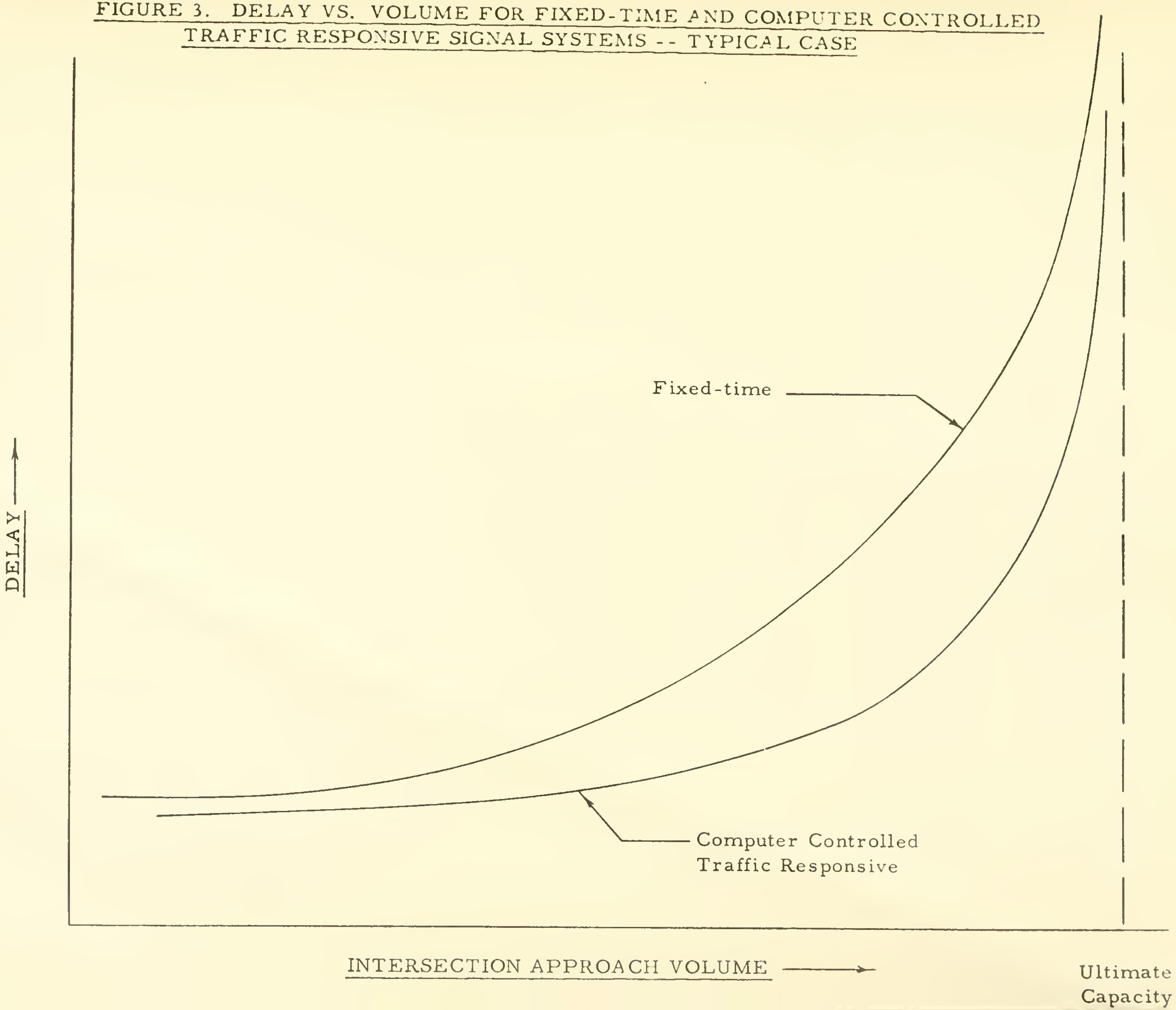
	Fixed-Time	Traffic Responsive
Intersection #1 -- A.M.	31	31
Intersection #1 --P.M.	52	42
Intersection #2 -- A.M.	52	33
Intersection #2 -- P.M.	40	36

It should be noted that Intersection #1 was usually well below capacity in the morning. This was one of the observations which led the authors of the report to conclude that traffic responsive control makes its greatest improvement as the traffic volume approaches the maximum capacity of an intersection. This is illustrated in Figure 3, in which typical delay vs. volume curves are drawn for fixed-time and computer controlled traffic responsive systems. The difference in delay between the two systems, for a given approach volume, would be represented by a vertical line drawn between the two curves. It can be seen that the length of this line (and consequently, the amount of improvement obtained by going from fixed-time to traffic responsive operation) would be a maximum at a volume approaching, but slightly less than, ultimate capacity.

It should also be noted that a traffic responsive system essentially becomes a fixed-time system at either extreme of operation. At high volumes, a traffic responsive system is pushed to the upper limits where the cycle is determined by the maximum allowable phase times. At this point, it behaves as any other fixed-time controller with the same cycle length and split, and it will break down in exactly the same way as volumes increase and delays become infinite. At the lower end, a traffic responsive system operates similarly to a fixed-time system whose cycle length is determined by the minimum allowable phase times. (This analysis refers to a single intersection, however; a traffic responsive system even at very low volumes may still perform better than a fixed-time system because of the better coordination patterns that the automatic system can establish).

The question also arises as to whether capacity is increased when progressions are improved. It is true that offset manipulation may sometimes be used to reduce congestion in critical areas caused by queues on short links. However, if capacity is defined as the maximum rate at which vehicles can move through an intersection, then, for given splits and cycle lengths, progressions, while they may reduce delay and queue lengths at relatively low approach volumes, will not affect the ultimate

FIGURE 3. DELAY VS. VOLUME FOR FIXED-TIME AND COMPUTER CONTROLLED TRAFFIC RESPONSIVE SIGNAL SYSTEMS -- TYPICAL CASE



capacity of an intersection. This is due to the fact that the capacity of an intersection is reached when vehicle headways are a minimum, and this minimum occurs when vehicles are released from a standing queue; since vehicles leaving an intersection tend to spread apart as they move down the street to the next intersection, headways in a moving platoon are larger than headways in a starting platoon.

In order to increase the capacity of an intersection, it would be necessary to vary the split from cycle to cycle to conform with the cycle to cycle variations in traffic volumes on each approach. Maximum capacity at an intersection would be obtained by varying both split and cycle length, but then this intersection could no longer be part of a progressive system.

5. DISCUSSION

a. Fixed-time traffic signal systems

The effectiveness of a fixed-time traffic signal system depends largely on the predictability of traffic flows. Where traffic flows are fairly predictable, and remain reasonably constant for certain periods of the day, a fixed-time traffic signal system can be made to perform quite well. The greater the variability of traffic throughout the day, the larger will be the number of dials (with their corresponding cycle lengths, splits, and offsets) that must be used to achieve the best performance. For example, it was determined in this study that the projected traffic flows through downtown Boston varied sufficiently to justify using the most flexible type of fixed-time equipment.

However, as traffic flows become less predictable, fixed-time traffic signal systems become less effective. (And, for the future downtown Boston network, the degree of day to day uniformity of traffic flows is still largely an unknown). The traffic volumes actually existing on the streets may be quite different from those for which the fixed-time system is set at a particular time. Where this is generally the case, effective traffic control can be achieved only if signal settings are established by the actual traffic flows. A traffic signal system which performs in this manner is called a traffic actuated or traffic responsive system.

b. Traffic actuated systems

The efficiency of a traffic actuated system will depend upon the variety of signal settings which can be put into effect, the extent to which the traffic flows are measured, and the techniques used for establishing signal settings to suit these measured flows. A simple way of proceeding to traffic actuated control is to provide dial change in a network of fixed-time controllers by means of the level of traffic volumes measured at one or more sampling points throughout the traffic signal network. Thus, prearranged fixed-time plans can be brought into play as they are actually required.

In principle this is the method used by almost every traffic responsive coordinated signal system presently in operation. The more popular of these systems offer a choice of six cycle lengths, five offsets, and three or four splits. Splits and offsets are set up individually at special controllers at each intersection. These controllers are wired to a central control unit which performs the function of establishing the cycle length and selecting from among the permissible split and offset patterns which have been set up on the street. Selection is done according

to the rate of count reported to the central control from sampling detectors in the streets. As the rate of count (volume) passes through predetermined levels established by the traffic engineer, the corresponding predetermined cycle, split, and offset pattern will be put into effect. To make a smooth transition from one group of settings to the next, the changes are introduced gradually and spread over a number of cycles. Traffic volumes at the sampling detectors are usually averaged over fairly long periods of time (up to 15 minutes or more) to prevent short term variations in traffic at the sampling points from adversely affecting the system as a whole. Some traffic actuated systems include provision for semi-actuated control at the crossings of minor and major streets and, more recently, provision for limited local variation of split at the intersection of major streets equipped with local detectors. These changes are not under the control of the central equipment.

While a number of these systems have been installed and apparently are giving satisfactory service, they do have a number of disadvantages, such as the loss of any investment in existing fixed-time equipment. Also, the grouping of signals for coordinated control depends upon the layout of the interconnecting wires, and each different grouping of signals requires a separate central control unit. Although central control initiates the changes in settings, most of the settings must be pre-set manually in the controllers in the streets. Then, too, it is not often that a few well-defined sampling points can be easily chosen. Attempts to correct this by using more and more sampling detectors often prove useless because the output of the detectors is grouped together and averaged. This has the effect of making the contribution of a single detector less important. If a large number of detectors are used, the average count may tend to remain constant for a long period of time, even though individual counts may be varying quite widely. Under these circumstances, the system would perform more like a fixed-time system than a traffic responsive system.

Another disadvantage of this kind of system is the lack of flexibility in implementing traffic signal settings. Offsets are maintained as a proportion of the cycle length. Thus, as the cycle is increased (due generally to increased traffic volumes), progression speeds are decreased. This concept is based on experience with freeway traffic flows where movements tend to be continuous. It is very frequently, however, invalid for urban traffic movements, which proceed in rather discontinuous fashion due to the platooning effects on traffic established by the traffic signal system. It has been found that in many cases platoon speeds do not depend significantly on traffic flows over a fairly wide range of volumes. This can be easily appreciated by considering the situation in moderate

to heavy traffic where weaving movements are restricted. In this case, the speed of the platoon is determined almost entirely by the speed at which the lead driver proceeds; i.e., it is independent of the number of vehicles following the driver. In fact, as traffic volumes increase, it is frequently desirable to increase the speed of progression in order to clear residual queues at an intersection before the arrival of the main platoon.

c. Computer controlled traffic signal systems

The most highly developed form of traffic signal system, and one which can be made free of all the limitations mentioned above, is that which uses a general purpose digital electronic computer as the central control element. With a computer controlled signal system, intersections can be coordinated into any variety of groups and sub-groups without limitation, and groups can be reorganized by the computer while control proceeds. Each phase of each signal can be made completely variable by the computer. Information from traffic detectors can be analyzed very minutely to uncover both the subtle as well as the gross changes in traffic movements. Several control strategies can be in operation at any given moment and used in such a way as to optimize local as well as the overall traffic flows. And computer control can be introduced into virtually any other form of control system, so that prior investment in other forms of control equipment need not be wasted. (A further practical advantage of the system is that the controller equipment in the streets can be left quite simple and thus relatively maintenance free).

In addition to the great versatility of applying control, a computerized signal system can offer a unique advantage not obtainable in any other way. During control the computer measures and otherwise generates a great deal of information on traffic flows and signal settings. This information is used not only in real time (that is, as control proceeds) for producing optimum signal settings, but it can also be readily recorded on magnetic tape for later analysis and study by the traffic engineering staff.

There are many ways of introducing electronic computer control to provide various levels of traffic actuated response. Going back for the moment to the simplest example of traffic actuated control described in the preceding section, an electronic computer could be used to provide dial switching in a multi-dial controller system. Here the use of the computer would be quite restricted and a very small computer would suffice. The function of the computer would be primarily to analyze, in a more meaningful way than could otherwise be achieved, the traffic movements

reported by a number of traffic detectors located in the streets. The flexibility of traffic signal settings would of course be limited to those available on the multi-dial system, but whatever signal patterns were available would be used in a more effective manner than could be achieved either by fixed-time switching or by switching on the basis of averaged counts alone.

If necessary, there are then many ways of proceeding from the simple computer system to the ultimate system where traffic control is virtually independent of any timing limitations imposed by the controller itself, and where timing equipment in the controller is used only as a standby safety device. If the system to be upgraded is kept general right from the outset, it is possible to pass from fixed-time control through various stages of computer control in such a way that the investment at any stage of the game is fully usable in a more expanded or more sophisticated version. The expandability of small computers and their functional compatability with larger computers makes this possible. For example, the small computer used in a simple system for analyzing traffic flows and changing controller dials, could be used in a larger and more sophisticated control system as part of the input/output mechanism which would be coupled to a larger and faster computer. Even the wire interconnect system used to coordinate multi-dial controllers could be so arranged at the outset as to easily form part of a computer controlled communications system at a later date.

In conclusion, the foregoing discussion illustrates how it is possible for Boston to proceed from a well developed fixed-time system, such as the one recommended in this report, to a very sophisticated computer controlled system, in such a manner as to preserve the initial investment throughout the various stages of development. Since the necessary interconnecting cable for a centrally controlled traffic signal system can be fairly readily installed in the downtown Boston study area, the City could confidently plan on proceeding at whatever pace was appropriate from a multi-dial fixed-time system to a computer controlled traffic signal system.

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6. APPENDIX A -

THE OPTIMIZATION CALCULATION

The optimization calculation of Traffic Research Corporation's optimization program can basically be described in the following manner. For every link in the system, there is input to the program a desired difference in offset ($\Delta\phi_p$). Due to geometrical constraints, however, the achieved difference in offset ($\Delta\phi_A$) is usually different from the desired difference in offset for most links in the system. To determine the optimum offset pattern, the program adjusts the offsets at each signalized intersection so as to minimize the weighted sum of the squares of the deviations between the desired and achieved differences in offset on each link in the system. The weighting factor for each link is equal to the product of the volume on that link (V) and an arbitrary "importance factor" (k) which can assume any value from 0.1 to 99.9 and which is used to indicate relative priorities of various routes in a system. Thus, for a system containing n links between signalized intersections, the program will

$$\text{minimize} \sum_{i=1}^{n} k_i V_i \left(\Delta\phi_{D_i} - \Delta O_{A_i}\right)^2$$

To illustrate, consider the following example from the downtown Boston system, run on a 120-second cycle between 7:30 and 8:30 A.M. On all intersections adjoining intersection #59 the optimized offsets output by the program are held constant. The results of the calculations to determine the optimized offset at intersection #59 are given in the following tables.

Link	Importance Factor (k)	Volume (V)	Desired Difference in Offset, sec. ($\Delta\phi_D$)	Achieved Difference in Offset, sec. ($\Delta\phi_A$)								
				Offset (%) at Intersection #59 =								
				27	32	35	36	37	38	39	42	47
59 to 53	0.3	150	10	39.8	33.8	30.2	29.0	27.8	26.6	25.4	21.8	15.8
59 to 58	50.0	600	118	-3.8	-9.8	-13.4	-14.6	-15.8	-17.0	-18.2	-21.8	-27.8
53 to 59	0.3	275	54	80.2	86.2	89.8	91.0	92.2	93.4	94.6	98.2	104.2
60 to 59	50.0	435	7	-22.4	-16.4	-12.8	-11.6	-10.4	-9.2	-8.0	-4.4	1.6
58 to 59	50.0	280	7	-36.2	-30.2	-26.6	-25.4	-24.2	-23.0	-21.8	-18.2	-12.2
59 to 60	50.0	315	5	-5.6	-11.6	-15.2	-16.4	-17.6	-18.8	-20.0	-23.6	-29.6

Let $Q_i = \left(\frac{k_i}{50}\right)\left(V_i\right)\left(\Delta\phi_{D_i} - \Delta\phi_{A_i}\right)^2$

= weighted square of the deviation between the desired and achieved differences in offset for link "i"

Link	Q								
	Offset (%) at Intersection #59 =								
	27	32	35	36	37	38	39	42	47
59 to 53	799	510	367	325	285	248	213	125	30
59 to 58	1,944	36,504	77,976	95,256	114,264	135,000	157,464	235,224	399,384
53 to 59	1,133	1,711	2,068	2,259	2,408	2,561	2,720	3,224	4,158
60 to 59	375,997	238,189	170,537	150,493	131,701	114,161	97,875	56,533	12,685
58 to 59	522,547	387,475	316,109	293,933	272,563	252,000	232,243	177,811	103,219
59 to 60	35,393	86,801	128,533	144,257	160,889	178,429	196,875	257,657	377,105
$\sum_{i=1}^{6} Q_i$	937,813	751,190	695,590	686,523	682,110	682,399	687,390	730,574	896,581

It can be seen from the second table that ΣQ (i.e., the weighted sum of the squares of the deviations between the desired and achieved differences in offset) is a minimum when the offset at intersection #59 is 37%. This is the value of the optimized offset output by the program.

7. APPENDIX B - TABLES AND DETAILED RESULTS

TABLE 1. SUMMARY OF RESULTS OF THE 54 RUNS OF THE OPTIMIZATION PROGRAM FOR THE DOWNTOWN BOSTON STUDY AREA[1]

			Importance Factors			Delay Propensity Factors		
Run #	Time Period	Cycle Length (sec.)	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes	Other Routes	Total System	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes
I	A.M.[2]	120	50.0	50.0	0.1-1.0	11.3	6.5	5.3
I-A	A.M.	120	1.0	1.0	1.0	8.8	8.3	12.0
II	Midday[3]	90	50.0	50.0	0.1-1.0	9.3	5.4	6.7
III	Midday	120	"	"	"	12.0		
IV	P.M.[4]	120	"	"	"	10.8	6.6	5.6
V	Evening[5]	60	"	"	"	7.3		
VI	Evening	90	"	"	"	10.0	5.1	6.0
VII	A.M.[6]	90	"	"	"	9.0		
VIII	A.M.[7]	120	"	"	"	7.7		
VII+VIII	A.M.[8]	90&120	"	"	"	11.0		
IX	P.M.[6]	90	"	"	"	9.1		
X	P.M.[7]	120	"	"	"	10.3		
IX+X	P.M.[8]	90&120	"	"	"	11.8		
XI	A.M.	120	50.0	0.1-1.0	0.1-1.0	8.9	6.5	11.7
XII	Midday	90	"	"	"	8.5	5.4	12.4
XIII	Midday	120	"	"	"	11.8		
XIV	P.M.	120	"	"	"	10.9	6.6	12.2
XV	Evening	60	"	"	"	7.1		
XVI	Evening	90	"	"	"	9.3	5.1	10.7
XVII	A.M.	120	50.0	5.0	0.1-1.0	11.0	6.5	6.6
XVIII	Midday	90	"	"	"	9.5	5.4	7.5
XIX	Midday	120	"	"	"	11.0	6.7	7.6
XX	P.M.	120	"	"	"	10.6	6.6	5.9
XXI	Evening	60	"	"	"	7.1	4.1	5.2
XXII	Evening	90	"	"	"	9.7	5.1	7.1

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[1] The system contains 68 signalized intersections, with 150 links to be optimized. Of these links, 39 are on 1st and 2nd order priority routes, and 33 are on 3rd and 4th order priority routes.

[2] 7:00 A.M. to 9:30 A.M.

[3] 9:30 A.M. to 3:30 P.M.

[4] 3:30 P.M. to 7:00 P.M.

[5] 7:00 P.M. to 12:00 Midnight

[6] 79 links only.

[7] 56 links only.

[8] Includes estimates of delays on the 15 connecting links.

TABLE 1. (Continued).

			Importance Factors			Delay Propensity Factors		
Run #	Time Period	Cycle Length (sec.)	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes	Other Routes	Total System	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes
XXIII	7:00-7:30 A.M.	120	50.0	5.0	0.1-1.0	11.1(11.9)[9]	8.1(7.7)[9]	8.3(9.3)[9]
XXIV	7:00-7:30 A.M.	110	"	"	"	9.7		
XXV	7:30-8:30 A.M.	120	"	"	"	11.0(12.5)[9]	6.8(7.1)[9]	8.7(8.8)[9]
XXVI	7:30-8:30 A.M.	130	"	"	"	12.1		
XXVII	8:30-9:30 A.M.	120	"	"	"	9.9(12.7)[9]	5.9(6.9)[9]	7.4(7.5)[9]
XXVIII	8:30-9:30 A.M.	110	"	"	"	11.3		
XXIX	3:30-4:00 P.M.	120	"	"	"	11.5(13.7)[10]	6.5(9.8)[10]	6.6(7.9)[10]
XXX	3:30-4:00 P.M.	100	"	"	"	10.2		
XXXI	4:00-5:30 P.M.	120	"	"	"	12.1(13.6)[10]	7.1(7.7)[10]	6.0(10.5)[10]
XXXII	4:00-5:30 P.M.	130	"	"	"	12.8		
XXXIII	5:30-7:00 P.M.	120	"	"	"	12.4(13.2)[10]	7.7(7.0)[10]	6.7(10.5)[10]
XXXIV	5:30-7:00 P.M.	100	"	"	"	11.2		
XXXV	9:30-12:00 A.M.	90	"	"	"	9.3(10.1)[11]	5.7(5.9)[11]	6.6(6.9)[11]
XXXVI	9:30-12:00 A.M.	80	"	"	"	8.7		
XXXVII	12:00-1:30 P.M.	90	"	"	"	9.7(10.8)[11]	5.6(5.5)[11]	7.5(9.3)[11]
XXXVIII	12:00-1:30 P.M.	80	"	"	"	8.7		
XXXIX	1:30-3:30 P.M.	90	"	"	"	9.9(10.1)[11]	5.3(5.5)[11]	7.8(8.8)[11]
XL	1:30-3:30 P.M.	80	"	"	"	8.9		
XLI	7:00-8:30 P.M.	90	"	"	"	9.8(10.7)[12]	4.9(6.3)[12]	6.7(7.3)[12]
XLII	7:00-8:30 P.M.	80	"	"	"	9.2		
XLIII	8:30-10:00 P.M.	90	"	"	"	9.6(11.1)[12]	5.0(5.3)[12]	7.0(7.6)[12]
XLIV	8:30-10:00 P.M.	70	"	"	"	8.3		
XLV	10:00-12:00 P.M.	90	"	"	"	9.5(11.3)[12]	5.2(5.8)[12]	6.4(7.8)[12]
XLVI	10:00-12:00 P.M.	70	"	"	"	8.2		

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[9] Using optimized offsets from Run XVII.
[10] Using optimized offsets from Run XVIII.
[11] Using optimized offsets from Run XX.
[12] Using optimized offsets from Run XXII.

TABLE 1. (Continued).

			Importance Factors			Delay Propensity Factors		
Run #	Time Period	Cycle Length (sec.)	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes	Other Routes	Total System	1st and 2nd Order Priority Routes	3rd and 4th Order Priority Routes
XLVII	A.M.	120	10.0	5.0	0.1-1.0	11.0 (13.2)[13]	6.7	6.0
XLVIII	Midday	90	"	"	"	9.3 (12.8)[12]	5.4	7.8
XLIX	Midday	120	"	"	"	11.5 (12.7)[10]	6.8	7.7
L	P.M.	120	"	"	"	10.6 (12.3)[13]	6.8	5.9
LI	Evening	60	"	"	"	7.2 (13.3)[10]	4.1	5.2
LII	Evening	90	"	"	"	10.1 (10.8)[11]	5.1	7.1
LIII	Midday	80	50.0	5.0	0.1-1.0	8.1		
LIV	Evening	80	"	"	"	8.6		

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[10] Using optimized offsets from Run XVIII.

[11] Using optimized offsets from Run XX.

[12] Using optimized offsets from Run XXII.

[13] Using optimized offsets from Run XIX.

TABLE 2. ESTIMATED DELAY PROPENSITY FACTORS FOR THE 68 SIGNALIZED INTERSECTION DOWNTOWN BOSTON STUDY AREA UTILIZING VARIOUS TYPES OF CONTROLLERS

	A.M.				P.M.							
	7:00-7:30	7:30-8:30	8:30-9:30	9:30-12:00	12:00-1:30	1:30-3:30	3:30-4:00	4:00-5:30	5:30-7:00	7:00-8:30	8:30-10:00	10:00-12:00
(A) 3-Dial (2 Splits and 2 Offsets per Dial)												
Cycle Length	110	120	120	80	80	80	120	120	120	80	80	80
Split Pattern #	1	2	3	4	4	4	5	5	5	6	6	6
Offset Pattern #	1	2	3	4	4	4	5	5	5	6	6	6
D.P.F.	9.7	11.0	9.9	10.6	10.4	10.5	14.1	14.5	15.1	11.3	10.7	10.9
(B)												
Cycle Length	120	120	120	80	80	80	100	120	100	80	80	80
Split Pattern #	1	1	1	2	2	2	3	4	5	6	6	6
Offset Pattern #	1	1	1	2	2	2	3	4	5	6	6	6
D.P.F.	14.5	13.6	12.2	10.6	10.4	10.5	10.2	12.1	11.2	11.3	10.7	10.9
(C) 3-Dial (1 Split & 3 Offsets per Dial)												
Cycle Length	120	120	120	80	80	80	120	120	120	80	80	80
Split Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
Offset Pattern #	1	2	3	4	5	6	7	8	9	4	5	6
D.P.F.	12.9	12.1	10.8	9.4	9.2	9.3	12.5	12.9	13.4	11.7	11.5	11.6
(D)												
Cycle Length	120	120	120	80	80	80	120	120	120	80	80	80
Split Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
Offset Pattern #	1	2	3	4	5	6	7	8	9	4	5	6
D.P.F.	12.9	12.1	10.8	15.9	15.2	15.5	12.5	12.9	13.4	10.0	9.5	9.7

TABLE 2 (Continued).

	A.M.				P.M.							
	7:00-7:30	7:30-8:30	8:30-9:30	9:30-12:00	12:00-1:30	1:30-3:30	3:30-4:00	4:00-5:30	5:30-7:00	7:00-8:30	8:30 10:00	10:00 12:00
(E) 3-Dial(3 Splits & 1 Offset per Dial)												
Cycle Length	120	120	120	80	80	80	120	120	120	80	80	80
Split Pattern #	1	2	3	4	5	6	7	8	9	4	5	6
Offset Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
D.P.F.	11.9	12.5	12.7	9.4	10.0	9.4	13.7	13.6	13.2	11.8	12.4	11.8
(F)												
Cycle Length	120	120	120	80	80	80	120	120	120	80	80	80
Split Pattern #	1	2	3	4	5	6	7	8	9	4	5	6
Offset Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
D.P.F.	11.9	12.5	12.7	15.8	16.3	16.6	13.7	13.6	13.2	9.9	10.3	10.5
(G) Conventional Traffic Responsive (Sampling Detector Operated, Several Cycle Lengths To Respond), Under Fixed-Time Operation (Total Of 6 Cycle Lengths, 5 Offsets, and 4 Splits)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	70	70
Split Pattern #	1	1	1	2	2	2	3	3	3	4	4	4
Offset Pattern #	1	2	1	3	3	3	4	4	4	5	5	5
D.P.F.	13.9	12.1	12.2	10.6	10.4	10.5	13.8	14.5	14.8	11.3	9.7	9.9
(H)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	70	70
Split Pattern #	1	1	1	2	2	2	3	3	3	4	4	4
Offset Pattern #	1	1	1	2	2	2	3	4	3	5	5	5
D.P.F.	13.9	13.6	12.2	10.6	10.4	10.5	13.8	12.9	14.8	11.3	9.7	9.9

TABLE 2 (Continued).

	A.M.				P.M.							
	7:00- 7:30	7:30- 8:30	8:30- 9:30	9:30- 12:00	12:00- 1:30	1:30- 3:30	3:30- 4:00	4:00- 5:30	5:30- 7:00	7:00- 8:30	8:30- 10:00	10:00 12:00
(I) Conventional Traffic Responsive, Under Fixed-Time Operation (Total of 6 Cycle Lengths, 5 Offsets, & 3 Splits)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	70	70
Split Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
Offset Pattern #	1	1	1	2	2	2	3	4	3	5	5	5
D.P.F.	13.9	13.6	12.2	10.6	10.4	10.5	13.8	12.9	14.8	12.4	11.2	11.3
(J)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	70	70
Split Pattern #	1	1	1	2	2	2	3	3	3	2	2	2
Offset Pattern #	1	2	1	3	3	3	4	4	4	5	5	5
D.P.F.	13.9	12.1	12.2	13.0	12.5	12.7	13.8	14.5	14.8	11.3	9.7	9.9
(K) 6-Dial (1 Split & 3 Offsets per Dial)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	80	80
Split Pattern #	1	2	2	3	3	3	4	5	4	6	6	6
Offset Pattern #	1	2	3	4	5	6	7	8	9	10	11	12
D.P.F.	9.7	12.1	10.8	9.4	9.2	9.3	11.2	12.1	12.2	10.0	9.5	9.7
(L) 6-Dial (5 Offsets & 4 Splits per Dial)												
Cycle Length	110	120	120	80	80	80	100	120	100	80	70	70
Split Pattern #	1	2	3	4	5	6	7	8	9	10	11	12
Offset Pattern #	1	2	3	4	5	6	7	8	9	10	11	12
D.P.F.	9.7	11.0	9.9	8.7	8.7	8.9	10.2	12.1	11.2	9.2	8.3	8.2

TABLE 3.

SUMMARY OF OFFSET DELAY ESTIMATES FOR THE 68 SIGNALIZED INTERSECTION DOWNTOWN BOSTON STUDY AREA UTILIZING THE VARIOUS TYPES OF CONTROLLERS

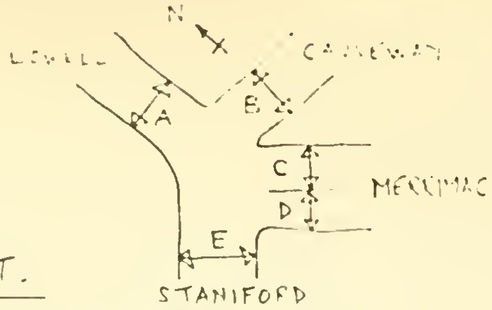
Offset Patterns*	Vehicle-Seconds of Offset Delay, 7:00 A. M. - 12:00 Midnight	Average Delay Propensity Factor	Vehicle-Hours of Delay per (17 hr.) Day	Vehicle-Hours of Delay per (17 hr. day, 5-day week) Year
A	16,788,900	11.6	4,664	1,212,530
B	16,397,470	11.4	4,555	1,184,260
C	16,083,350	11.2	4,468	1,161,580
D	18,954,300	13.1	5,265	1,368,920
E	16,642,770	11.5	4,623	1,201,980
F	19,740,440	13.7	5,483	1,425,700
G	17,124,400	11.9	4,757	1,236,760
H	17,001,130	11.8	4,723	1,227,860
I	17,357,740	12.0	4,822	1,253,610
J	18,338,940	12.7	5,094	1,324,480
K	15,048,310	10.4	4,180	1,086,820
L	14,041,570	9.7	3,900	1,014,110

*A, B -3-Dial (2 Splits & 2 Offsets Per Dial)
C, D -3-Dial (1 Split & 3 Offsets Per Dial)
E, F -3-Dial (3 Splits & 1 Offset Per Dial)

G, H, I, J - Conventional Traffic Responsive Under Fixed -Time Operation (Total of 6 Cycle Lengths, 5 Offsets, and Either 4 (G, H) or 3 (I, J) Splits)

K - 6-Dial (1 Split & 3 Offsets Per Dial)
L - 6-Dial (5 Offsets & 4 Splits Per Dial)

TABLE 4. SAMPLE OPERATION SCHEDULE



Intersection No. 1

Location Merrimac St. - Staniford St. - Lowell St. - Causeway St.

	TIMING FOR AUTOMATIC OPERATION (%)												OFFSET (%)	CYCLE LENGTH
7:00 A.M. - 7:30 A.M.	29	33	35	41	47	53	92	94	97	100			18	110
7:30 A.M. - 8:30 A.M.	25	28	30	36	42	47	92	94	97	100			31	120
8:30 A.M. - 9:30 A.M.	31	34	36	42	48	53	92	94	97	100			17	120
9:30 A.M. - 12:00 A.M.	33	38	40	49	58	65	89	91	96	100			98	80
12:00 A.M. - 1:30 P.M.	34	39	41	50	59	66	89	91	96	100			15	80
1:30 P.M. - 3:30 P.M.	35	40	42	51	60	67	89	91	96	100			32	80
3:30 P.M. - 4:00 P.M.	35	39	41	48	55	61	91	93	97	100			17	100
4:00 P.M. - 5:30 P.M.	39	42	44	50	56	61	92	94	97	100			71	120
5:30 P.M. - 7:00 P.M.	41	45	47	54	61	67	91	93	97	100			33	100
7:00 P.M. - 8:30 P.M.	34	39	41	50	59	66	89	91	96	100			48	80
8:30 P.M. - 10:00 P.M.	33	39	41	51	61	70	87	90	96	100			52	70
10:00 P.M. - 12:00 P.M.	31	37	40	50	60	69	87	90	96	100			54	70
MERRIMAC ST.	R-LA-RA	Y	R	R	R	R	R	R	R	R				
LOWELL ST.	G	Y	R	R	R	R	R	R	R	R				
STANIFORD ST.	R	R	R	R	R	R	VA-RA	VA-RA	Y	R				
CAUSEWAY ST.	R	R	R	R	R	R	VA-LA	VA-LA	Y	R				
C.W. - A, C	DW	DW	DW	W	W	W	W	FDW	FDW	FDW				
C.W. - B, E	DW	DW	DW	W	FDW	FDW	DW	DW	DW	DW				
C.W. - D	DW	DW	DW	W	W	FDW	DW	DW	DW	DW				
C.W. -														

KEY

G = Green
LA = Left Arrow
RA = Right Arrow
VA = Vertical Arrow
Y = Yellow (or Amber)
R = Red
W = Walk
DW = Don't Walk
FDW = Flashing Don't Walk

TABLE 5. LIST OF ROUTES FOR WHICH SPACE-TIME CHARTS HAVE BEEN PRESENTED TO THE B. R. A.

1. New Atlantic Avenue -- Dorchester Avenue.
   South Market St. ; State St. ; Milk St. ; India St. ; High St. ; Northern Ave. ; Congress St. ; Summer St.

2. Dorchester Avenue -- New Atlantic Avenue
   Summer St. ; Congress St. ; Northern Ave. ; High St. ; India St. ; Milk St. ; State St. ; South Market St.

3. Columbus Avenue -- Stuart Street -- Kneeland Street.
   Arlington St. ; Charles St. ; Tremont St. ; Washington St. ; Harrison Ave. ; Kingston St. ; Lincoln St. ; South St.

4. Kneeland Street -- Stuart Street -- Eliot St.
   South St. ; Lincoln St. ; Kingston St. ; Harrison Ave. ; Washington St. ; Tremont St. ; Charles St.

5. Washington Street -- Court Street -- Cambridge Street.
   State St. ; Tremont St. ; Sudbury St. ; Chardon St. ; Staniford St.

6. Cambridge Street -- Tremont St.
   Staniford St. ; Chardon St. ; Sudbury St. ; Court St. ; Beacon St. ; Bromfield St. ; Park St. ; Exeter St. ; Boylston St. ; Stuart St.

7. Lowell Street -- Merrimach Street -- Congress Street.
   Staniford St. ; Chardon St. ; Sudbury St. ; State St. ; Milk St. ; Franklin St. ; High St.

8. Congress Street -- Devonshire Street -- Otis Street -- Kingston Street.
   State St. ; Milk St. ; Franklin St. ; Summer St. ; Essex St.

9. Harrison Avenue -- Chauncy Street -- Washington Street.
   Essex St. ; Summer St. ; Franklin St. ; Milk St. ; Water St. ; State St.

10. School Street -- Milk Street.
    Washington St. ; Chauncy St. ; Devonshire St. ; Congress St. ; Pearl St. ; Broad St. ; India St. ; New Atlantic Ave.

11. Commercial Street -- India Street -- Franklin Street -- Bromfield Street.
    Milk St. ; Pearl St. ; Congress St. ; Devonshire St. ; Chauncy St. ; Washington St. ; Tremont St.

TABLE 5. (Continued)

12. Summer Street.
    Atlantic Ave.; Purchase St.; High St.; Otis St.; Chauncy St.

13. Boylston Street -- Essex Street.
    Charles St.; Tremont St.; Washington St.; Chauncy St.; Kingston St.; High St.; South St.

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